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Original Investigation

Conventional and electronic cigarettes (e-cigarettes) have different smoking characteristics

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Abstract

Introduction: Electronic cigarettes or e-cigarettes are marketed as tobacco-free nicotine delivery devices that have received little laboratory evaluation. In this study, the smoking properties of conventional and e-cigarettes were compared by examining the vacuum required to produce smoke (conventional cigarettes) or aerosol (e-cigarettes) and the density of the smoke/aerosol over time.

Methods: Vacuum was measured using a manometer coupled to a smoking machine. The density of aerosol or smoke was measured spectrophotometrically. E-cigarettes were subjected to smoke-out experiments in which vacuum and aerosol density were measured until each cartridge was exhausted.

Results: The vacuum required to smoke conventional cigarettes varied among the eight brands tested. Lights and ultra-light brands required stronger vacuums to smoke than unfiltered and regular filtered brands. Except for one brand, higher vacuums were required to smoke e-cigarettes than conventional brands. Smoke/aerosol density was stable for conventional brands and for e-cigarettes over the first 10 puffs; however, aerosol density of e-cigarettes dropped during subsequent smoking, and higher vacuums were required to produce aerosol as the puff number increased. While conventional cigarettes were uniform in their smoking behavior within brands, vacuum and density varied within brands of e-cigarettes.

Discussion: Generally, e-cigarettes required stronger vacuums (suction) to smoke than conventional brands, and the effects of this on human health could be adverse. The amount of aerosol produced by e-cigarettes decreased during smoking, which necessitated increasing puff strength to produce aerosol. The decreased efficiency of aerosol production during e-cigarette smoking makes dosing nonuniform over time and calls into question their usefulness as nicotine delivery devices.

Introduction

E-cigarettes, which are marketed as a relatively new type of tobacco-free nicotine delivery device, consist of a cartridge

containing nicotine and propylene glycol, an atomizer, and a battery (Pauly, Li, & Barry, 2007; Wollscheid & Kremzner, 2009). These consumer products have also been referred to as electronic nicotine delivery systems (World Health Organization, 2009). When a smoker draws air through the cigarette, an airflow sensor activates the battery that turns the tip of the cigarette red to simulate smoking and heats the atomizer to vaporize the propylene glycol and nicotine. Upon inhalation, the aerosol vapor delivers a dose of nicotine into the lungs of the smoker, after which, residual aerosol is exhaled into the environment.

While produced mainly in China, e-cigarette use has rapidly proliferated worldwide (Pauly et al., 2007). E-cigarettes may be less harmful than conventional cigarettes since they do not burn tobacco and therefore do not deliver the numerous chemicals and toxicants found in conventional cigarette smoke. They have also been advertised as smoking cessation devices that can be used with cartridges containing progressively lower doses of nicotine, although the Electronic Cigarette Association no longer promotes this idea (<http://www.ecassoc.org/the-facts-about-electronic-cigarettes/>).

In spite of these apparently attractive features, little is known about the health benefits and risks of e-cigarettes. Only three studies have examined the contents of the aerosol produced by e-cigarettes. One, done by the Food and Drug Administration (FDA), reached the conclusion that e-cigarettes contain carcinogens, albeit at lower levels than conventional cigarettes (Westenberger, 2009). Perhaps more disturbing, in a sampling of a relatively small number of cartridges, the FDA found that one cartridge contained 1% diethylene glycol, a known toxicant that has been involved in prior mass poisonings (Ballentine, 1981; Westenberger). The second analytic study, funded by a leading e-cigarettes manufacturer, concluded that e-cigarettes were safer than conventional brands, mainly because the levels of carcinogens in e-cigarettes are reduced (Laugesen, 2008). The third study did not find measurable levels of polycyclic aromatic hydrocarbons in e-cigarette aerosol (Leondiadis, 2009). The lack of consensus among these studies combined with the paucity of work on e-cigarettes demonstrates that we have insufficient data to evaluate the health effects associated with e-cigarette usage and that further research on e-cigarettes is urgently needed (Flouris &

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Oikonomou, 2010). Moreover, the effectiveness of e-cigarettes as nicotine delivery devices has been called into question by two recent studies in which the levels of nicotine in the serum of e-cigarette smokers were much lower than in serum from the same individuals when they smoked conventional cigarettes (Bullen et al., 2010; Eissenberg, 2010).

In preliminary trials, we observed that some brands of e-cigarettes were difficult to smoke, possibly due to their relatively small air intake holes and the overall density of the interior of e-cigarettes in comparison with relatively porous tobacco-containing cigarettes. We also noticed that the density of the aerosol produced by e-cigarettes diminished during smoking. These preliminary observations suggested to us that e-cigarettes smoked very differently than conventional brands.

The purpose of this study was to compare the smoking properties of conventional and e-cigarettes using a smoking machine. Specifically, we tested the hypotheses that e-cigarettes would require stronger vacuums to smoke than conventional brands and that e-cigarettes would provide diminishing amounts of aerosol as they are smoked. The smoking characteristics of e-cigarettes have not previously been reported but are of interest as they could affect smoking behavior, nicotine dosage, and usage.

Materials and methods

Cigarettes

Conventional cigarettes were purchased from local retail dealers and included Merit Ultra Lights, Marlboro Ultra Lights, Marlboro Lights, Marlboro Reds, Camel unfiltered, Camel Lights, Camel filtered, and Pall Mall unfiltered cigarettes (Supplementary Table I). Merit and Marlboro cigarettes were manufactured by Philip Morris Inc. (Richmond, VA), while Camel and Pall Mall cigarettes were produced by R J Reynolds Tobacco Company (Winston-Salem, NC). To maintain constant temperature and humidity during storage, cigarette packs were stored at 4 °C until opened, after which they were stored in a desiccator until smoked.

E-cigarette starter kits and cartridges were purchased either on the Internet or from a local dealer. Starter kits included battery, charger, power cord, atomizer, and cartridges. The following brands were tested: Liberty Stix (Liberty Stix, LLC, Cleveland, OH), Crown Seven's Hydro Kit (Crown Seven Shop, Scottsdale, AZ), NJOY (Sottera Inc., Scottsdale, AZ), and Smoking Everywhere's Gold Kit (Smoking Everywhere, Inc., Sunrise, FL). A VapCigs starter kit was purchased from a local vendor. The VapCigs experiments were done using tobacco-flavored refill cartridges that the vendor claimed were refills for the VapCigs e-cigarettes; however, the cartridge box was labeled J-118 replacement filters. Additional details on e-cigarette brands are given in Supplementary Table I. Electronic cigarettes and their cartridges were stored at room temperature until smoked.

Smoking machine setup

Analytic smoking of conventional and e-cigarettes was conducted using a puffer box built at the University of Kentucky (Lexington, KY; Supplementary Figure 1). The puffer box was connected via Cole Parmer MasterFlex Tygon tubing (Vernon Hills, IL) to a

MasterFlex peristaltic pump (3 Amp, 115Vac, 50/60 Hz; Barnart Company, Barrington, IL; Model #7520-00). The line between the puffer box and the pump contained two untapered T connectors from VWR International (West Chester, PA). The connector closest to the puffer box held the conventional or electronic cigarette. The second connector was attached to an upright U-shaped water manometer built at the University of California (Riverside, CA). The manometer was used to measure vacuum in the line drawing a puff from each cigarette. All joints in the system were sealed with parafilm, and the peristaltic pump was warmed up for a minimum of 15 min before smoking began.

Smoking protocol

Each smoking trial was conducted with a fresh conventional cigarette or an electronic cigarette containing a fresh unused cartridge. Conventional cigarettes were smoked to 5 mm from the edge of the filter or 23 mm from the edge of the cigarette in the case of unfiltered brands. Each e-cigarette was smoked using a fully charged battery with its brand-specific cartridge and atomizer. To mimic an active smoker, the peristaltic pump speed was reduced to zero until just before every puff was taken at which time pump speed was turned up to the desired level. The puffer box was calibrated to draw 2.2-s long puffs of smoke at a frequency of 1 puff/min. Both types of cigarettes were smoked starting at the lowest pump speed that enabled them to produce smoke or aerosol. The setting on the peristaltic pump remained the same for each consecutive puff unless aerosol density dropped below 0.05 absorbance units in which case the pump speed was increased by one increment on the pump dial to enable smoking to continue.

The strength of the vacuum required to smoke conventional and e-cigarettes was measured using an U-shaped vertical water manometer (Supplementary Figure 1). Measurements of water displacement (mm H₂O) from both sides of the manometer were taken for each puff during the 2.2-s puff interval. Density of the aerosol or smoke was measured from the exhaust tube on the peristaltic pump using a Bausch & Lomb Spectrophotometer (120 Volts, 0.9 Amps, Rochester, NY). Puffs of smoke or aerosol were collected in a spectrophotometer tube, and absorbance was immediately read at 420 λ.

Comparison of conventional and e-cigarettes

Conventional cigarettes were smoked completely (7–11 puffs depending on the brand), and e-cigarettes were smoked for their first 10 puffs. The vacuum required to produce smoke or aerosol was measured every puff, while density of the smoke and aerosol was measured every other puff. Three trials were conducted for each brand of conventional and e-cigarettes. All e-cigarette brands, except for VapCigs, were included in this experiment.

E-cigarette smoke-out experiment

To determine how vacuum and density change during smoking and how many puffs each brand of e-cigarette could produce, e-cigarettes were smoked until their cartridges were exhausted, and vacuums and densities were measured during the smoke-out interval. Three trials were conducted per e-cigarette brand, each with a fresh unused cartridge. Measurements of vacuum

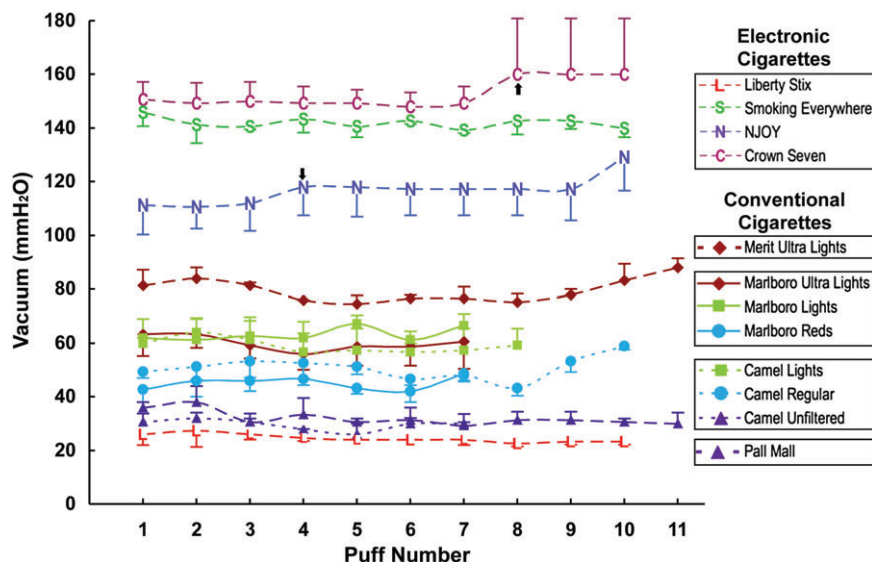


Figure 1. Average vacuum required to smoke conventional versus e-cigarettes. The number of puffs varied among conventional brands due to variation in the smokable length of each brand. All e-cigarettes were smoked for the first 10 puffs of fresh unused cartridges. All cigarettes were smoked at the lowest pump setting that permitted smoking. Arrows indicate when pump speed had to be increased to keep e-cigarettes producing aerosol. Each point is the mean \pm SD of three experiments.

and aerosol density were taken every puff and every 10th puff, respectively. If aerosol density dropped below 0.05 absorbance units, the peristaltic pump speed was increased by turning up the pump dial one interval. Smoking was stopped when the peristaltic pump reached its maximum speed (850 rpm), and the aerosol density was below 0.05 absorbance units. Cartridges were considered exhausted either at the beginning of consecutive puffs below 0.05 absorbance units or when smoking was stopped.

Results

Vacuum required to smoke conventional and e-cigarettes

The purpose of this experiment was to test the hypothesis that e-cigarettes require greater vacuum to smoke than conventional brands (Figure 1; Table 1). Eight brands of conventional cigarettes were smoked, and the vacuum created during each puff was measured with a manometer (Figure 1). The minimum peristaltic pump speed that could be used to smoke the cigarettes (250 rpm) remained constant throughout the experiment for each brand (Table 1). Average vacuums produced during smoking differed among the brands of cigarettes and ranged from 30 ± 3 (Camel unfiltered) to 80 ± 5 (Merit; Table 1). Vacuums remained relatively constant over the entire smoking interval with slight increases during the final few puffs for Camel regular and Merit Ultra Lights (Figure 1). Unfiltered brands (Pall Mall and Camel) required the lowest vacuums to smoke, presumably because they lacked filters and therefore presented the least resistance to airflow. However, an increase in the vacuum was needed to smoke the filtered conventional brands. Moreover, vacuum strength increased progressively from regular filtered cigarettes (Marlboro Red and Camel regular) to light cigarettes (Marlboro Lights and Camel Lights) to ultra-light

(Merit Ultra Lights; Table 1). Marlboro Lights and Marlboro Ultra Lights were similar in their vacuum requirements. Merit Ultra Lights required a vacuum that was considerably higher than other conventional brands (Figure 1).

Four brands of e-cigarettes were evaluated in a similar experimental design (Figure 1; Table 1). Each e-cigarette was smoked for 10 puffs with a fresh cartridge to simulate smoking a single conventional cigarette. Unlike conventional cigarettes, the pump speeds required to begin smoking each brand of e-cigarette were variable (Table 1). Within a brand, the pump speed required to begin smoking was the same for all brands except NJOY (Table 1). Since smoking different brands of e-cigarettes required different settings on the peristaltic pump, each cigarette was initially smoked using the lowest pump speed that would enable the cigarette to produce aerosol. Vacuums measured by the manometer during smoking also varied for the e-cigarettes (Figure 1; Table 1) and for the initial puff ranged from 26 ± 4 mm H₂O (Liberty Stix) to 151 ± 6 mm H₂O (Crown Seven; Figure 1). During smoking, vacuums remained similar to the initial puff except for Crown Seven and NJOY, which both required an increase in vacuum via an increase in pump speed (arrows in Figure 1) to continue aerosol production in at least one of the three trials. The average vacuums for 10 puffs for the e-cigarette brands ranged from 25 ± 3 (Liberty Stix) to 153 ± 12 (Crown7) mm H₂O (Table 1). The vacuum required to smoke Liberty Stix was at the low end of the range observed for conventional cigarettes. However, three brands of e-cigarettes required a vacuum that was well above the vacuums needed to smoke conventional brands.

Smoke and aerosol density produced during 10 puffs

To determine how density varied during the smoking of a single cigarette (approximately 10 puffs), smoke or aerosol were

Table 1. Comparison of smoking properties of conventional and electronic cigarettes

| Brand | Pump speed (rpm) | | Average vacuum (mm H ₂ O) | Average smoke and aerosol density |
|-----------------------|------------------|----------|--------------------------------------|-----------------------------------|
| | Initial | Average | | |
| Liberty Stix | 250 ± 0 | 250 ± 0 | 25 ± 3 | 0.5 ± 0.2 |
| Smoking Everywhere | 600 ± 0 | 600 ± 0 | 142 ± 4 | 0.2 ± 0.1 |
| NJOY | 707 ± 46 | 725 ± 40 | 117 ± 10 | 0.1 ± 0.1 |
| Crown Seven | 530 ± 0 | 537 ± 21 | 153 ± 12 | 0.1 ± 0.1 |
| Merit Ultra Lights | 250 ± 0 | 250 ± 0 | 80 ± 5 | 0.2 ± 0.1 |
| Marlboro Ultra Lights | 250 ± 0 | 250 ± 0 | 60 ± 6 | 0.2 ± 0.1 |
| Camel Lights | 250 ± 0 | 250 ± 0 | 59 ± 6 | 0.2 ± 0.1 |
| Marlboro Lights | 250 ± 0 | 250 ± 0 | 63 ± 5 | 0.3 ± 0.1 |
| Camel Regular | 250 ± 0 | 250 ± 0 | 51 ± 5 | 0.3 ± 0.1 |
| Marlboro Reds | 250 ± 0 | 250 ± 0 | 45 ± 4 | 0.5 ± 0.2 |
| Camel Unfiltered | 250 ± 0 | 250 ± 0 | 30 ± 3 | 0.9 ± 0.4 |
| Pall Mall Unfiltered | 250 ± 0 | 250 ± 0 | 32 ± 4 | 0.5 ± 0.2 |

collected and their absorbance measured in a spectrophotometer (Figure 2; Table 1). For conventional brands, smoke density generally increased during the course of smoking a cigarette (Figure 2). The only exception was Marlboro Lights that showed a dramatic drop in density at the last puff. The experiment with Marlboro Lights was repeated, and the same results were obtained (data not shown). With the exception of Marlboro Lights, density correlated well with the type of cigarette and decreased going from unfiltered to ultra-light filtered brands. Average density (absorbance) for the conventional brands ranged from 0.2 ± 0.1 for Merit, Marlboro Ultra Lights, and Camel Lights to 0.9 ± 0.4 for Camel unfiltered (Table 1). Camel unfiltered produced a density that was outside the range of the other brands,

including Pall Mall, which is also unfiltered. Within each brand, there was not much variation among cigarettes (Figure 2).

All brands of e-cigarettes produced initial and average densities that were similar to the initial and average densities of the conventional brands (Figure 2; Table 1). However, Liberty Stix produced an initial and average density that was considerably higher than the other brands of e-cigarettes (Table 1). Unlike the conventional brands, the e-cigarette aerosol density did not increase over the 10-puff interval, except for Liberty Stix, which increased slightly at puffs 7 and 9. The SDs for Liberty Stix are larger than for the other brands because one Liberty Stix cartridge produced a higher density than the other two. When the

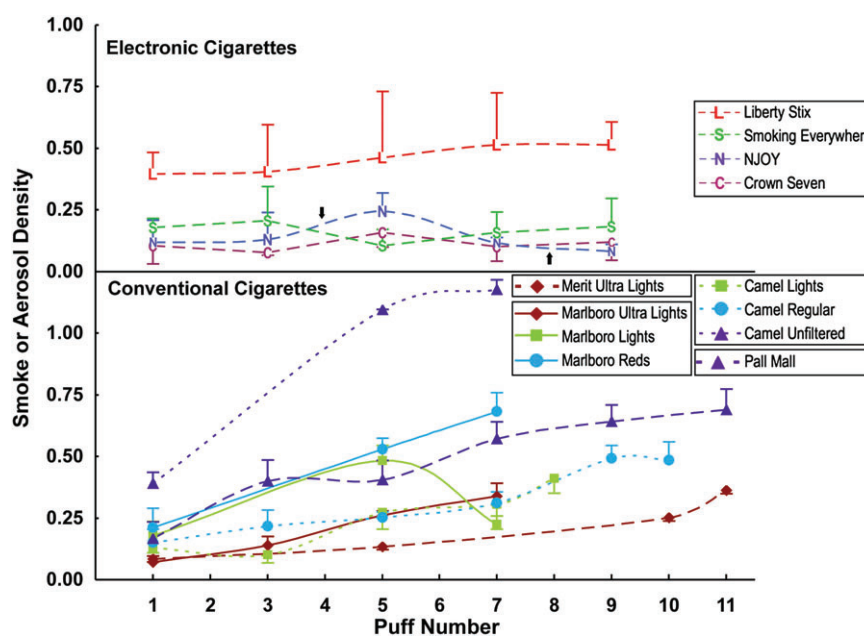


Figure 2. Aerosol or smoke density for conventional and e-cigarettes. Conventional or e-cigarettes were smoked as described in Figure 1. At certain intervals, the density (absorbance) of the smoke or aerosol was measured using a spectrophotometer. Arrows indicate when pump speed had to be increased to keep e-cigarettes producing aerosol. Each point is the mean \pm SD of three experiments.

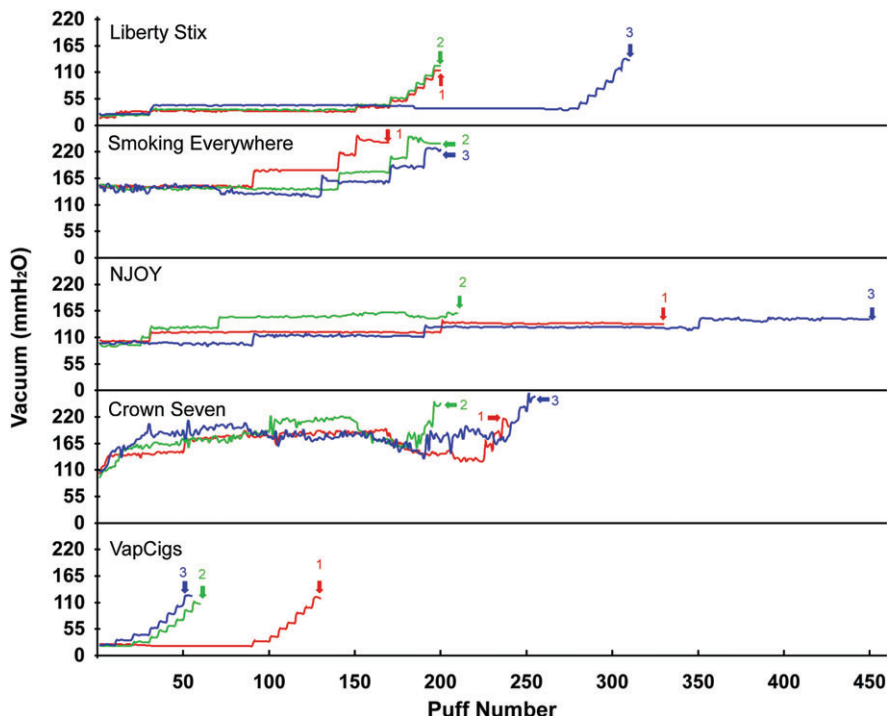


Figure 3. Changes in vacuum during e-cigarette smoke out. Five brands of e-cigarettes were smoked as described in Materials and Methods section until they no longer produced aerosol. Pump speed was increased when absorbance read less than 0.05 units. Data are shown for three individual cartridges for each brand. Arrows indicate cartridge per trial number. In color version: Trial 1 = red, Trial 2 = green, and Trial 3 = blue.

two lower density Liberty Stix cartridges were averaged, their mean was still higher than the average density of the other e-cigarette brands (data not shown).

Vacuum changes during e-cigarettes smoke-out experiments

E-cigarettes are reported to last for about 200 puffs (Figure 3; Table 2). Since the above experiments only included the first 10 puffs from each cartridge, follow-up smoke-out experiments were done to test the hypothesis that over time, the vacuum required to smoke e-cigarettes increases, while the aerosol density decreases. VapCigs were also included in this experiment. The VapCigs starter kit came with four brand-specific cartridges that were difficult to smoke and required the maximum setting on the peristaltic pump (850 rpm) to produce initial aerosol (data not shown).

All brands of e-cigarettes required increases in pump speed during the course of the smoke-out interval (Table 2—compare initial and average pump speeds). The first time that pump speed needed to be increased varied considerably with brand (Table 2). For example, on average, Liberty Stix required an increase in pump speed after only 24 ± 12 puffs, while Smoking Everywhere required an increase after 121 ± 26 puffs. Changes in the vacuum required to produce aerosol from the five brands of e-cigarettes during smoke-out are shown for each of three cartridges in Figure 3. Increases in peristaltic pump speed appear as step-up increases in vacuum on the graphs. Rapid sequential step-ups at the end of most lines indicate the e-cigarette cartridge was nearing the end of its usefulness. Two of the

Liberty Stix cartridges had almost identical vacuum patterns, while the third cartridge smoked considerably longer than the first two (Figure 3.). The cartridges with similar patterns were from the same cartridge pack, while the longer smoking cartridge was from a different pack, which might explain the observed differences in length of smoking. Smoking Everywhere required increases in vacuum during smoking of each cartridge. Two of these cartridges (#2 and #3) were similar, while cartridge #1 smoked a shorter time and required a higher vacuum earlier during smoke-out. NJOY cartridges all required step-ups in vacuum during smoking. Crown Seven vacuum measurements were the noisiest of the brands tested, as indicated by the chatter in the graph. The noise was caused by a sudden initial increase in vacuum followed by a relaxation to a lower vacuum within the 2.2-s puff interval (initial vacuum is plotted). Other brands did not show this property and did not exhibit noise in their vacuum readings. For Crown Seven, which required the strongest average vacuum of the five brands tested (Table 2), vacuum increased until about puff 150 after which vacuum in all three cartridges declined (while pump speed remained constant before the cartridge became exhausted). The VapCigs replacement cartridges performed very poorly. All showed rapid step-ups in vacuum soon after smoking started, indicating that aerosol was no longer being produced even at the highest vacuum on the peristaltic pump (Figure 3). For Liberty Stix and VapCigs, average vacuums over puffs that produced aerosol during smoke outs were within the range of the conventional brands (Table 1). However, average vacuums over puffs that produced aerosol during smoke outs for Smoking Everywhere, Crown Seven, and NJOY were well above the range of the conventional cigarettes (Tables 1 and 2).

Table 2. Smoking properties of electronic cigarettes during smoke out

| Brand | Pump speed (rpm) | | First pump speed increase ^a | | Average vacuum ^b (mm H ₂ O) | Average aerosol density ^b (absorbance) |
|--------------------|------------------|-----------|--|-------------|--|---|
| | Initial | Average | Pump speed (rpm) | Puff number | | |
| Liberty Stix | 250 ± 0 | 384 ± 119 | 350 ± 0 | 24 ± 12 | 34 ± 6 | 0.4 ± 0.3 |
| Smoking Everywhere | 600 ± 0 | 650 ± 78 | 680 ± 0 | 121 ± 26 | 158 ± 26 | 0.2 ± 0.2 |
| NJOY | 627 ± 46 | 764 ± 83 | 707 ± 46 | 49 ± 36 | 128 ± 18 | 0.2 ± 0.1 |
| Crown Seven | 530 ± 0 | 577 ± 63 | 600 ± 0 | 114 ± 71 | 174 ± 23 | 0.3 ± 0.2 |
| VapCigs | 250 ± 0 | 411 ± 200 | 350 ± 0 | 41 ± 44 | 21 ± 2 | 0.3 ± 0.2 |

Note. ^aValues when the first time pump speed was increased during smoke out.

^bVacuum, aerosol density, and total smokable puffs were averaged over puffs prior to cartridge exhaustion.

Aerosol density during e-cigarette smoke-out experiments

To test the hypothesis that aerosol density decreases during smoking, the density of the aerosol produced by e-cigarettes was measured during the smoke-out experiments (Figure 4; Table 2). Over the interval when aerosol was produced, the average aerosol density for the e-cigarettes was within the density range produced by the conventional brands (Tables 1 and 2). In Figure 4, open symbols indicate points when peristaltic pump speed was increased. Pump speed was increased if the aerosol density fell below 0.05 absorbance units. For all cartridges, aerosol density decreased at least once by puff #50. While increasing the pump speed increased the aerosol density up to a point, there was a general trend for density to decrease with time. As the cartridges became exhausted, consecutive increases in pump speed failed to increase aerosol density (Figure 4, consecutive open symbols

toward end of most lines). Density remained consistently higher for longer with Liberty Stix than with the other four brands. Also density patterns for Liberty Stix were similar among cartridges. Smoking Everywhere, like Liberty Stix, showed a gradual tailing off in density over time. In contrast, densities for NJOY and Crown Seven were quite variable and cycled up and down over the smoke-out interval. This variation occurred both within individual cartridges and between cartridges within a brand (NJOY and Crown Seven; Figure 4). Two of the VapCigs replacement cartridges (#2 and #3) produced almost no aerosol, while the first cartridge produced aerosol for only about 50 puffs.

Average puff number for e-cigarettes

The aerosol density data were used to estimate the average maximum puff number for each brand of e-cigarettes (Figure 4; Table 3). Cartridges were considered exhausted when consecutive

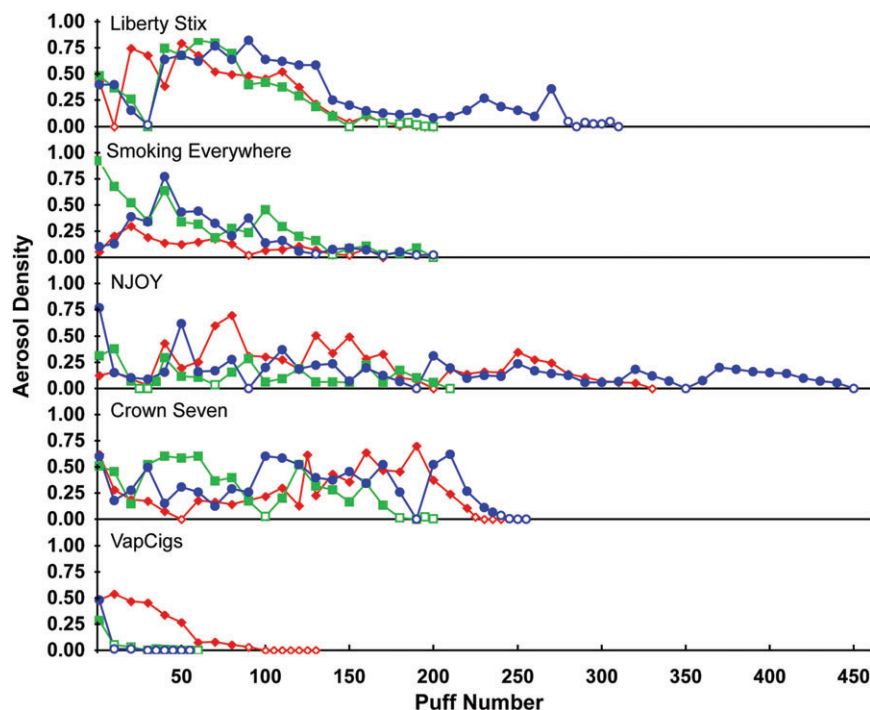


Figure 4. Changes in aerosol density during e-cigarette smoke-out experiments. Aerosol density was measured every 10th puff, unless there was no visible aerosol in which case density was read every 5th puff. Open symbols show when the peristaltic pump speed had to be increased to attempt to increase aerosol density above 0.05 absorbance units. Data are shown for three individual cartridges for each brand.

Table 3. Total puff number for conventional and electronic cigarettes

| Brand | Total smokable puffs ^a |
|-----------------------|-----------------------------------|
| Liberty Stix | 197 ± 64 |
| Smoking Everywhere | 177 ± 15 |
| Crown Seven | 208 ± 34 |
| NJOY | 313 ± 115 |
| VapCigs | 30 ± 43 |
| Merit Ultra Lights | 11 ± 0 |
| Marlboro Ultra Lights | 7 ± 0 |
| Camel Lights | 8 ± 0 |
| Marlboro Lights | 7 ± 0 |
| Camel Regular | 10 ± 1 |
| Marlboro Reds | 7 ± 0 |
| Camel Unfiltered | 7 ± 0 |
| Pall Mall Unfiltered | 11 ± 0 |

^aVacuum, aerosol density, and total smokable puffs were averaged over puffs prior to cartridge exhaustion.

increases in pump speed failed to produce aerosol. While conventional brands consistently produced the same puff number within brands, the e-cigarette puff numbers varied significantly within brands (Table 3). Smoking Everywhere was the least variable (177 ± 15 puffs), while NJOY showed the greatest variation (313 ± 115 puffs). The VapCigs replacement cartridges produced very few puffs of aerosol, possibly because they were not correctly matched to the e-cigarette. Because density drops off during the smoking interval, the puffs at the end of the interval were of lower density for each brand.

To determine why NJOY lasted so much longer than the other brands, the volume of each cartridge reservoir, which holds the e-cigarette fluid, was estimated. NJOY had a reservoir that was almost five times the volume of Liberty Stix (Supplementary Figure 2, Supplementary Table 1), which could account for the increased number of puffs obtained with NJOY. Interestingly, Liberty Stix and Crown Seven produced about the same number of puffs on average, but Liberty Stix had a reservoir that was three times smaller than Crown Seven (Supplementary Figure 2, Supplementary Table 1), indicating that puff number is influenced by factors in addition to reservoir size.

Discussion

Three brands of e-cigarettes required a stronger vacuum to smoke than conventional brands. Moreover, as e-cigarettes were smoked out, the vacuum required to produce aerosol increased with increasing puff number. The density of the aerosol produced by e-cigarettes decreased, in most cases fairly rapidly, as the e-cigarette was smoked. Aerosol density could be increased by increasing the peristaltic pump speed up to a point after which even the highest pump speed did not produce any aerosol. In the case of NJOY, liquid was still observed in the spent cartridges even when aerosol was not being produced. These data suggest that delivery of nicotine is not uniform across the total number of puffs produced by e-cigarette cartridges and

that most brands of e-cigarettes will require stronger inhalation than conventional brands.

Vacuum data on NJOY, Smoking Everywhere, and Crown Seven support our hypothesis that e-cigarettes require more suction to smoke than conventional brands. This conclusion is supported by two observations. First, the speed on the peristaltic pump required to smoke these three brands of e-cigarettes was much higher (530–707 rpm) than the speed (250 rpm) needed to smoke the conventional cigarettes. Second, the vacuum on the e-cigarettes during smoking as measured by the manometer was considerably higher for Crown Seven, NJOY, and Smoking Everywhere than for the conventional cigarettes. Interestingly, Liberty Stix grouped with the conventional cigarettes in terms of its vacuum requirements. The lower vacuum needed to smoke Liberty Stix was probably due to the presence of larger air intake holes in this cigarette (data not shown) and a smaller cartridge reservoir (Supplementary Figure 2), which combined to decrease resistance to airflow. In spite of its small cartridge, Liberty Stix out lasted Smoking Everywhere apparently because of the low vacuum needed to produce aerosol with Liberty Stix. All brands of e-cigarettes required stronger vacuum to smoke as the cartridge was used up. The diminishing amounts of aerosol that were produced during smoking coupled with the need to increase puff strength to obtain aerosol are two factors that could lead users to compensatory smoking as has been seen with other harm reduction products (Strasser, Lerman, Sanborn, Pickworth, & Feldman, 2007). Our data further indicate that compensatory smoking of the conventional brands would be influenced by both the nicotine content of regular versus light cigarettes plus the increased vacuum required to smoke the lighter brands. The long-term health consequences of having to puff harder to activate and smoke e-cigarettes have not been studied but needs to be considered in evaluating their safety.

The variations we observed in aerosol density suggest that nicotine dosage decreases as e-cigarettes are used and that stronger puffs are needed to sustain density, until eventually the cartridge is exhausted. Even with stronger puffs, density was quite variable in some brands, suggesting that dosing would not be uniform over the smoke-out interval. Nonuniform dosing coupled with the need for stronger inhalation may in part explain why humans who smoke e-cigarettes have low levels of nicotine in their blood after smoking (Bullen et al., 2010; Eissenberg, 2010). E-cigarettes cartridges are often said by manufacturers to be equivalent to a certain number of conventional cigarettes. However, this information might be misleading as e-cigarette aerosol density was not uniform over the smoke-out interval. Therefore, while the first 10 puffs of an e-cigarette may be similar to a conventional cigarette, later puffs were highly variable in aerosol density and may not duplicate smoking of conventional brands. Even though one e-cigarette cartridge may smoke for 200 puffs, cartridges do not smoke uniformly for those 200 puffs and therefore may not duplicate nicotine delivery of individual conventional cigarettes.

E-cigarettes were more variable in their smoking properties than conventional brands. Conventional cigarettes smoked at a fixed pump speed that was identical across brands, while e-cigarette brands smoked at different pump speeds, which needed to be increased to continue smoking. Moreover, the

time at which increased pump speed was needed to sustain aerosol production varied both within and between e-cigarette brands. Even within brands, there was some variation in the pump speed needed to smoke the e-cigarettes (NJOY). Within brands of conventional cigarettes, smoke density was very similar during the smoking interval. In contrast, aerosol density for the e-cigarettes was variable within brands during the smoke-out experiment, suggesting that dosing is more erratic with e-cigarettes. Within brands, the total number of puffs produced by conventional brands was identical, while this metric was highly variable for e-cigarettes both between and within brands. Finally, cartridges that were not labeled “VapCigs” but were sold as replacements for VapCigs produced very few puffs of aerosol, showing that cartridges are not interchangeable among manufacturers, contrary to what vendors may say at the time of sale. Variations in smoking parameters between brands would be expected for numerous reasons relating to cigarette and filter design. However, variations within brands, as was often observed for the e-cigarettes, indicate that quality control procedures used to manufacture these products are lax. These data further demonstrate that future studies with e-cigarettes will need to take into account both brand-to-brand and cartridge-to-cartridge variation.

In summary, our data show that for the e-cigarette brands tested, (a) stronger puffing is required to smoke most e-cigarettes than to smoke conventional brands (Figure 1, Table 1), (b) puff strength had to be increased as puff number increased (Figure 3, Table 2), (c) aerosol density decreased fairly rapidly as puff number increased (Figure 4), and (d) smoking characteristics, such as vacuum and density, vary considerably both within and between brands of e-cigarettes (Figures 3 and 4). Taken together, these data demonstrate the need for further studies on e-cigarettes and detailed health evaluations of their users so that appropriate regulations and manufacturing practices are implemented to protect human health.

Supplementary Material

Supplementary Table 1 and Figures 1 and 2 can be found at *Nicotine and Tobacco Research* online (<http://www.ntr.oxfordjournals.org/>).

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Declaration of Interests

None declared.

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